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# Anisotropic Mechanical Behavior of Ni-base Alloy Weld Metal Considering Crystal Orientation Distribution

Yoshiki Mikami<sup>a\*</sup>, Keisuke Sogabe<sup>a</sup>, Satoru Nishikawa<sup>b</sup>,  
Takahiro Sakai<sup>a</sup> and Masahito Mochizuki<sup>a</sup>

<sup>a</sup>Graduate School of Engineering Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan

<sup>b</sup>Japan Power Engineering and Inspection Corporation, 14-1 Benten-cho, Tsurumi-ku, Yokohama 230-0044, Japan

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## Abstract

Microscopic stress distribution in clad weld metal of Ni-base alloy was calculated. Simulation model of a columnar grain aggregate was generated based on a crystal orientation measurement result by electron backscatter diffraction method. Microscopic stress much higher than applied macroscopic stress was observed when load was applied along transverse direction of columnar grain growth direction. On the other hand, homogeneous microscopic stress was obtained in a columnar grain model when macroscopic stress was applied in columnar grain growth direction. The difference caused from anisotropic crystalline orientation distribution of weld metal, and is important in the evaluation of microscopic stress distribution in weld metal.

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## 1. Introduction

Prediction of occurrence of SCC (stress corrosion cracking) is essential to ensure safe operation of nuclear power plants. Recently, SCCs are more observed in weld metal due to improvement of base materials. In order to evaluate occurrence of cracks, evaluation of stress distribution in weld metal is important especially in a microscopic scale.

Generally, weld metal exhibit solidification microstructure and weld residual stress is also acting on it. Weld metal of austenitic stainless steels and Ni-base alloys tend to form anisotropic crystal orientation

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\* Corresponding author. Tel.: +81-6-6879-7561; fax: +81-6-6879-7561  
E-mail address: [mikami@mapse.eng.osaka-u.ac.jp](mailto:mikami@mapse.eng.osaka-u.ac.jp)

caused from its solidification microstructure:  $\langle 1\ 0\ 0 \rangle$  direction coincide with columnar grain growth direction. As the crystal orientation affects the mechanical properties, the anisotropic aspect of weld metal will leads to the anisotropic mechanical response of weld metal when external loading is applied.

In this paper, anisotropic mechanical behavior of Ni-base alloy weld metal was discussed. At first, anisotropy of weld metal in terms of crystal orientation was evaluated by EBSP (electron backscatter pattern) method. The result was introduced into finite element model of aggregate of columnar grains. Then, tensile loading was applied to the model and microscopic stress distribution was calculated considering crystal plasticity.

## 2. Crystal Orientation of Clad Weld Metal of Ni-base Alloy

A weld specimen was fabricated by shielded metal-arc welding to prepare weld metal. A groove of 6 mm depth and 13 mm width was machined on an Alloy 600 plate and weld bead was deposited. Welding current, arc voltage and welding speed were 130 A, 25 V, 1 mm/s, respectively. Shown in Fig. 1 is a crystalline orientation map measured on the top surface of the cladded weld metal. As seen from the figure, direction  $\langle 1\ 0\ 0 \rangle$  is mainly observed along the direction perpendicular to the surface of the weld metal.

In weld metal, grains grow along maximum temperature gradient direction therefore columnar grains are formed. In addition,  $\langle 1\ 0\ 0 \rangle$  direction is the priority growth orientation in face-centered materials such as Ni-base alloy, longitudinal direction of the columnar grain coincides with  $\langle 1\ 0\ 0 \rangle$  direction. Schematic illustration of crystal orientation of weld metal in a cross section is shown in Fig. 2. The priority growth direction is perpendicular to isothermal lines during solidification process of weld metal. Orientation  $\langle 1\ 0\ 0 \rangle$  is the priority growth direction, columnar grains in weld metal grows along the direction indicated by arrows in Fig. 2. The tendency is more obvious in cladded weld metal in which columnar grains grow mainly along surface direction.

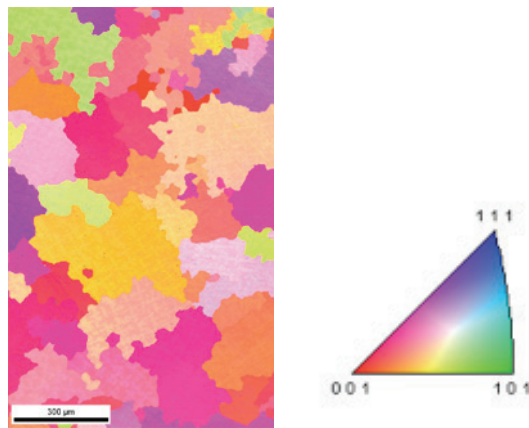


Fig. 1. Crystal orientation map of the surface of the cladded weld metal.

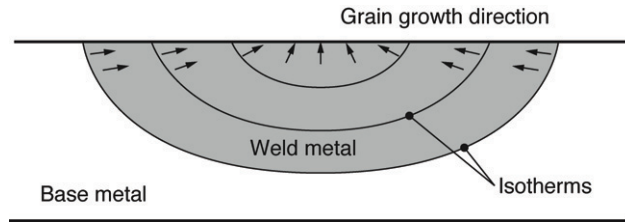


Fig. 2. Schematic illustration of the priority growth direction of columnar grains of Ni-base alloy.

### 3. Numerical Simulation Model

A simulation model of an aggregate of columnar grains is shown in Fig. 3. Ten elements are arranged per an edge; totally 1000 elements are included in the model. Applying crystalline orientation to each element, the model represents polycrystalline behavior. In order to take into consider the effect of crystalline orientation, a theory of crystal plasticity was incorporated into the simulation model. The numerical simulation was performed by commercial finite element software Abaqus incorporating user-subroutine UMAT to consider crystal plasticity [1, 2].

In order to model an aggregate of columnar grains, a group of elements was formed using 10 elements in  $z$  direction. The group of 10 elements represents 1 columnar grain. Therefore, 100 columnar grains are included within the model shown in Fig. 3. Crystalline orientation was applied to each columnar grain.

In the most ideal case,  $\langle 1\ 0\ 0 \rangle$  direction completely align along  $z$  direction at the center of the weld metal as shown in Fig. 2. However, in actual cases, the direction inclines from  $z$  direction. Therefore, inclination of  $\langle 1\ 0\ 0 \rangle$  direction from  $z$ -axis was varied in the simulation model. The inclination angle is denoted by  $\Phi$ , and was varied in the following three cases:  $\Phi = 0^\circ$ ,  $\Phi = 0^\circ$  to  $10^\circ$  and  $\Phi = 0^\circ$  to  $30^\circ$ . Schematic illustration for inclination of  $\langle 1\ 0\ 0 \rangle$  direction from  $z$ -axis is shown in Fig. 4. The crystalline orientation of a columnar grain is not uniquely defined by  $\Phi$ , the rotational change around  $\langle 1\ 0\ 0 \rangle$  direction also exists. The rotational change of crystalline orientation around  $\langle 1\ 0\ 0 \rangle$  direction was randomly defined. In addition, a simulation model in which crystalline orientation was completely randomly applied to the 1000 elements shown in Fig. 3 was also generated for comparison. The model does not include columnar grains, so that it corresponds to polycrystalline base metal.

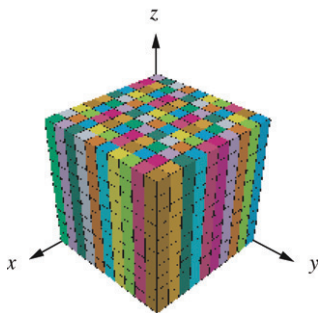


Fig. 3. A simulation model of an aggregate of columnar grains.

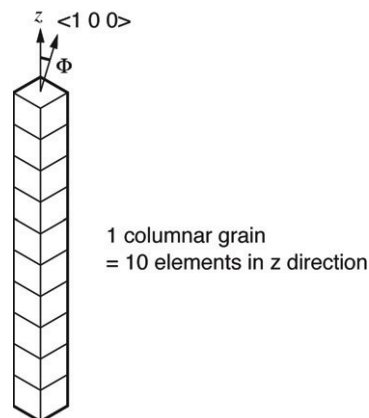


Fig. 4. Schematic illustration of  $\Phi$  defined for a columnar grain.

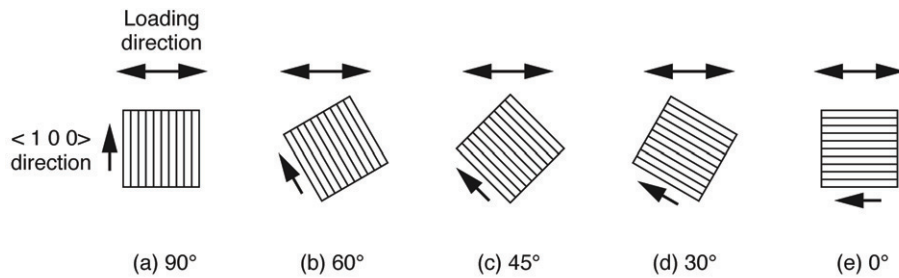


Fig. 5. Boundary condition applied to the model. Angle between loading direction and  $\langle 1\ 0\ 0 \rangle$  direction, (a)  $90^\circ$ ; (b)  $60^\circ$ ; (c)  $45^\circ$ ; (d)  $30^\circ$ ; (e)  $0^\circ$

Displacement corresponding to 1% macroscopic tensile strain was applied to the surface of the model in  $x$  direction as shown in Fig. 5(a). In addition, in order to discuss the effect of loading direction, the relationship between loading direction and columnar grain growth direction was varied as shown in Figs. 5(b) to (e).

#### 4. Microscopic Stress Distribution in Ni-base Alloy Weld Metal

Stress obtained by the simulation model is plotted in Fig. 6(a). The horizontal axis shows stress obtained in each element and the vertical axis shows the number fraction. The average stress macroscopically applied to the model is about 300 MPa, and stress in each element distribute as shown in Fig. 6(a) due to crystalline orientation distribution. As seen from the figure, the distribution is quite similar between columnar grain models ( $\Phi = 0^\circ$ ,  $0^\circ$  to  $10^\circ$  and  $0^\circ$  to  $30^\circ$ ) and the random orientation model. This is because crystalline orientation in  $x$ - $y$  plane is randomly distributes both in columnar grain models and in the random orientation model. The result indicates that an aggregate of columnar grains like clad weld metal shows mechanical response like ordinary polycrystalline material when loading is applied in vertical direction of columnar grain growth direction. Microscopic stress obtained in the model exceeds macroscopically applied stress due to crystalline orientation distribution.

Results for the simulation cases where the angle between  $\langle 1\ 0\ 0 \rangle$  orientation and loading direction varied are shown in Figs. 6(b) to 6(e). For  $\Phi = 0^\circ$  model, as the angle between  $\langle 1\ 0\ 0 \rangle$  direction and loading direction decrease, the stress value obtained in the model converges to about 300 MPa, the macroscopic stress level. The columnar grain model have crystalline orientation of  $\langle 1\ 0\ 0 \rangle$  in loading direction, and random orientation in transverse direction to loading direction.

In addition, when the anisotropy of the columnar grain model decreases, that is, condition concerning  $\Phi$  changes from  $\Phi = 0^\circ$  to  $10^\circ$  and  $0^\circ$  to  $30^\circ$ , the distribution moves to the case of random distribution. The result is quite reasonable and it is important that anisotropy of clad weld metal still remains even in case  $\Phi = 0^\circ$  to  $30^\circ$  when loading applied in the longitudinal direction of columnar grains.

Considering the correspondence to actual case, the occurrence of high stress is more possible when the aggregate of columnar grains are subjected to loading in transverse direction; the situation would occur in clad weld metal. On the contrary, the case where the columnar grain growth direction and loading direction coincides, stress observed in the model is converges to a value; the situation would be found in high-energy beam weld metal of thick section.

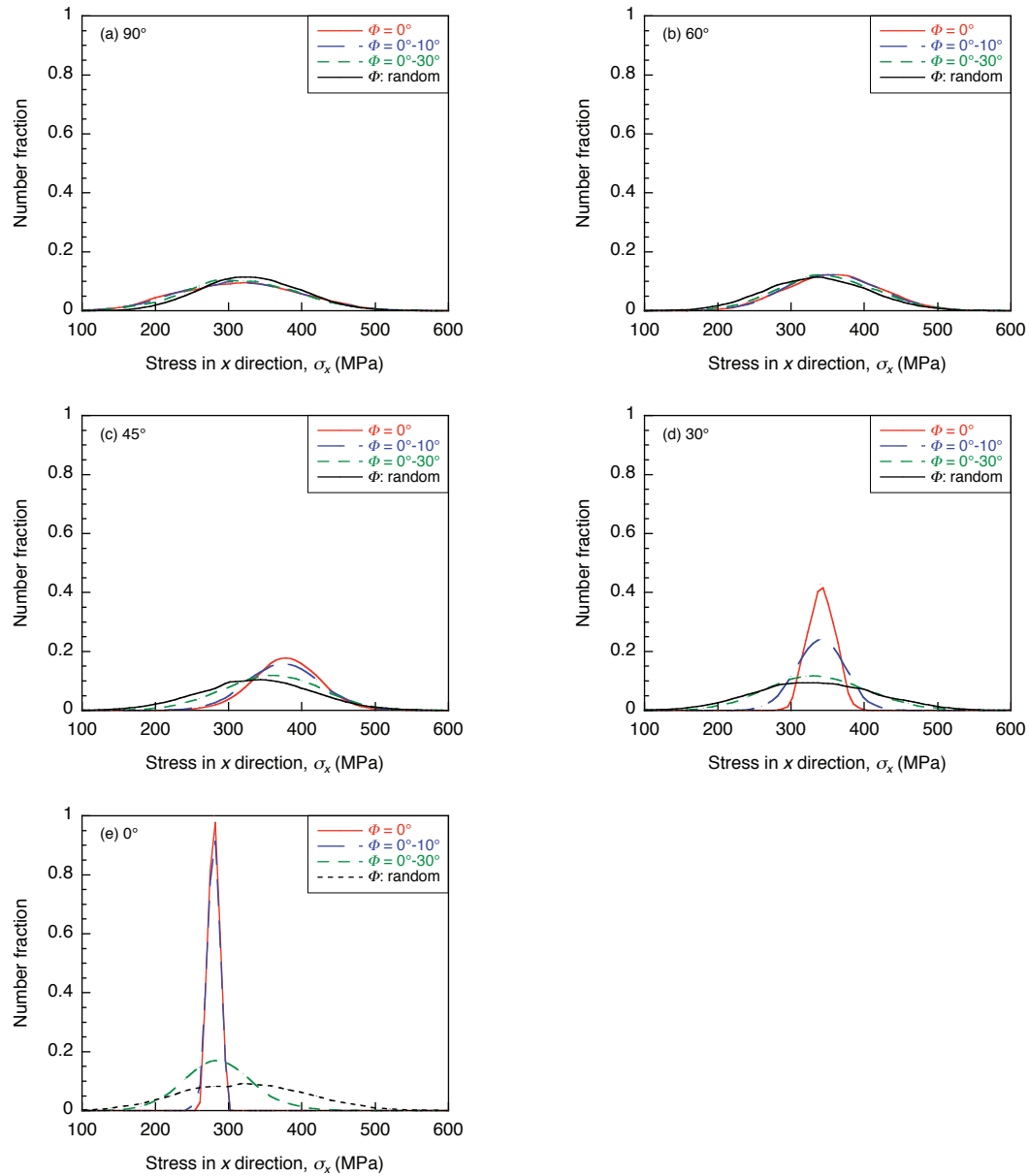


Fig. 6. Effect of columnar grain growth direction on microscopic stress. Angle between loading direction and  $\langle 100 \rangle$  direction, (a) 90°; (b) 60°; (c) 45°; (d) 30°; (e) 0°

## 5. Conclusion

In this paper, anisotropic mechanical behavior of Ni-base alloy clad weld metal was discussed by numerical simulation considering the theory of crystal plasticity.

1. Microscopic stress generated in the columnar grain model was in the range of 100 MPa to 500 MPa while macroscopically applied stress was about 300 MPa when the loading direction is vertical to  $\langle 1\ 0\ 0 \rangle$  orientation. The situation commonly occurs when clad weld metal is subjected to external loading, so that the microscopic stress concentration is important in the evaluation of stress field.
2. When the external loading is applied in the columnar grain growth direction, microscopic stress generated in loading direction was homogeneous. However, when the anisotropy of weld metal decreases, high microscopic stress region occurs in the simulation model.

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